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APPLICATION FOR UNITED STATES LETTERS PATENT

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TITLE: INTER-REGULATOR CONTROL OF MULTIPLE ELECTRIC POWER SOURCES

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BACKGROUND

[0001] Electrical power for vehicles, including automobiles, trucks and buses, is typically supplied by alternator-battery systems. The alternator is usually driven by mechanical means to generate electric power. The power output of the alternator is controlled by a voltage regulator, which senses the voltage output of the alternator and adjusts the alternator magnetic field or rectification control to maintain a desired value of alternator output voltage.

[0002] The electrical power for the vehicles may be used in heavy duty, high current applications, such as operating vehicular air conditioning. In such applications, a single alternator may not produce sufficient electric power. To generate additional power, two or more alternators may be connected in parallel when the total system electrical load exceeds the power generating capacity of a single alternator.

[0003] If two or more alternators are required in a system, each alternator typically has its own voltage regulator. The voltage control is therefore performed independently for each alternator. In this instance, even if the multiple alternators are identical in every respect, there remain different voltages present in the system due to variety of factors. One factor is different voltages present in the system due to cabling and connection voltage drops that change with electrical load. For example, an alternator's location within the system requires interconnecting cabling and connectors that may affect the voltage at the alternator's output. Another factor is differences in alternator performances. For example, an alternator's performance may be affected by its operating temperature. Temperature variations in the system may result in the alternators operating at different temperatures, thereby resulting in different alternator outputs. These temperature variations may be due to internal or external cooling airflow dynamics or the proximity to nearby sources of heating or cooling.

[0004] As a result, when load changes occur, the portion of the total electrical load supplied by each alternator is not predicable or constant. Rather, the

instability of the system is manifested by unstable output voltages and unbalanced distribution of electrical load as load changes occur. This instability is a condition called "hunting" and is caused by the portion of the total load supplied by each individual alternator not being constant. Another undesirable effect of the instability is that one alternator in the system assumes most, or potentially all, of the total system load. In such cases the overworked alternator may suffer premature failure.

[0005] Solutions to the problem of multiple alternators have been attempted. One such attempt is disclosed in U.S. Patent No. 5,723,972 (Bartol et al.) in which two or more alternators are electrically connected in parallel across a battery and load. A corresponding number of electronic voltage regulators individually control the alternators, with one regulator that is specially configured as the master and the other regulators are configured as followers to receive a signal from the master regulator. The master regulator only senses the voltage across the battery and generates a master control signal for use in both the master regulator and all follower regulators to generate the power to the electric loads and maintain regulated voltage.

[0006] What is needed is better inter-regulator control of multiple alternators.

SUMMARY

[0007] In one aspect of the invention, a system and method for controlling multiple sources of electric power is provided. The system may include multiple voltage regulator – source of electric power combinations with the sources of electric power being electrically connected in parallel. The sources of electric power may include alternators or fuel cells. One of the regulators may be the master regulator and the remaining regulator(s) may be the follower regulator(s). The master regulator may produce signals for its respective source of electric power and produce signals for follower regulator(s) based on the sensed output of at least one source of electric power and on operational characteristics of at least one source of electric power. One example includes the master regulator producing signals for the follower regulators based on sensing the output and the operating characteristics of its respective alternator. The operational characteristics of the sources of electric power may include: (1) designed operational characteristics, such as output rating; and (2) variable operating characteristics, such as ambient temperature, operating temperature, speed, and accumulated operational life.

[0008] In another aspect of the invention, a regulator is disclosed with the functionality of the master regulator and the functionality of the follower regulator combined into a universal regulator device. In this manner, the design and maintenance of the system is simplified. Rather than having two separate regulators, one for a master regulator and another for a follower regulator, a single universal regulator may be used. Determining whether a universal regulator operates as a master or a follower regulator may occur before operation (such as by hardwiring the regulator via a switch or by programming to operate as a master or follower regulator) or during operation (such as by an arbitration process between regulators to determine the master and follower regulators). Once a master regulator has been determined, such as by arbitration, this determined regulator may remain as the master regulator for the duration of the present period of operation. Alternatively, if this determined regulator is not the master regulator

for the duration of the present period of operation, another regulator in the system may be the master regulator for at least a portion of the present period of operation. The regulators may also alternate between master and follower status based on a predetermined duty cycle or default condition. With this scheme, the primary point of voltage reference for the system may shift to different points of voltage measurement in the system (such as each possible point of voltage measurement in the system), thereby ensuring that the system voltage is, on average and over an extended period of operation, regulated at all possible points in the system.

[0009] In still another aspect of the invention, follower regulator(s) may verify the instructions and commands sent from the master regulator. The verification of the instructions may be based on the follower regulator sensing the output of its associated source of electric power. Further the verification by the follower regulator may be based on the operational characteristics of its associated source of electric power.

[0010] In yet another aspect of the invention, a diagnostic tool may be used to evaluate the regulator-alternator system. The diagnostic tool may be used either during testing of the system or during operation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is an exemplary block diagram of a voltage regulator – alternator combination.

[0012] FIG. 2 is an exemplary block diagram of multiple voltage regulator – alternator combinations as shown in FIG. 1 with the alternators electrically connected in parallel.

[0013] FIG. 3 is an exemplary block diagram of a single voltage regulator controlling multiple alternators, with the alternators electrically connected in parallel.

[0014] FIG. 4 is a graph of time versus output current for two of the alternators shown in FIG. 2.

[0015] FIG. 5 is an exemplary flow diagram of operation of the multiple voltage regulator – alternator combinations shown in FIG. 2.

[0016] FIG. 6 is an exemplary flow diagram for determining the signals for the master and follow regulators at block 74 of FIG. 5.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Turning to the drawings, wherein like reference numerals refer to like elements, FIG. 1 shows an exemplary block diagram of a voltage regulator – alternator combination. Alternator 30 is a conventional alternator and may comprise a field coil 42, windings 44, and a rectifier 46. The field coil 42 may be supplemented by, or replaced by, a permanent magnet. The windings 44 may include three power output windings so that the alternator is a three-phase machine, though the present invention is not so limited. Alternator 30 may further include a rectifier 46 that rectifies the alternating current (AC) outputs of power output windings into direct current (DC). The rectifier 46 may comprise diodes or other types of switching devices. For an alternator which comprises a permanent magnet, the rectifier may comprise a silicon controlled rectifier (SCR). Further, the control of the output of the alternator may comprise controlling the SCR, as shown by the arrow into block 46. Alternator 30 produces output power at output 40 when field coil 42 modulates changes in electromagnetic coupling within the power output windings 44. Further, an energy storage device, such as a battery or a capacitor, may be connected to output 40.

[0018] Alternator 30 is merely one example of a source of electric power. Other types of generators may be used as a source of electrical power. Further, a fuel cell may be used as a source of electric power. The fuel cell may be paired with a regulator, with the regulator regulating the amount of electric power generated by the fuel cell. Specifically, the regulator may control either a valve or a heating element in the fuel cell, thereby regulating the amount of electric power generated by the fuel cell.

[0019] The voltage regulator 10 includes a processor 20 and a memory device 22. The processor 20 and memory device 22 may be integral with one another. For example, the processor 20 and memory device 22 may be housed in a single device, such as a microcontroller. Alternatively, the processor 20 and memory device may be separate components, such as a microprocessor in combination with read-only memory. Further, the voltage regulator 10 may be a separate component

within the vehicle, or may be a part of a system controller of the vehicle, such as an engine control unit or an electrical system monitor.

[0020] Voltage regulator also includes signal conditioning interface 23 which receives analog or digital feedback signals from the alternator. One of these signals may be the sensed feedback voltage 34 of the alternator. The sensed feedback voltage 34 may be taken at the terminal voltage of the alternator to which the regulator is connected, as shown in FIG. 1. Alternatively, the sensed feedback voltage may be taken at the terminal voltage of another alternator or at the connection to the energy storage device (such as a battery, capacitor, etc.). The sensed feedback voltage 34, though shown as a single line in FIGS. 1 and 2, may include a single line for the power output or may include multiple lines including a power output and a ground line. Another input to the signal conditioning interface 23 may be output 36 received from the alternator. This output 36 may comprise some or all of the operational characteristics of the alternator. For example, output 36 may include the current operational characteristics, such as current ambient temperature, current operating temperature, and speed of alternator 30. Moreover, output 36 may include designed operational characteristics, such as output rating, if memory 22 does not have the designed operational characteristics stored therein.

[0021] Voltage regulator 10 further includes communication interface 24. Communication interface 24 enables the receipt of communications input and the delivery of communications output for voltage regulator 10. For example, communication interface 24 may include an input/output line 38 for communication with other regulators. As discussed in FIG. 2, the regulator may operate as a master regulator or as a follower regulator. As a master regulator, the communication interface outputs via line 38 the signal to control the follower regulator(s). Moreover, as a master regulator, the communication interface inputs via line 38 the acknowledgement by the follower regulator(s) of receipt of the signal. Similarly, as a follower regulator, the communication interface inputs via line 38 the signal from the master regulator and outputs the acknowledgement via line 38. As shown in FIG. 1, line 38 is a single, bi-directional digital or analog line. Alternatively, a bi-directional (parallel) bus structure or unidirectional or bi

directional line (serial) digital or analog structure may be implemented. Voltage regulator 10 may further include driver 26. For alternators which have a current driver included, driver 26 may comprise a switch, such as a silicon controlled rectifier (SCR) or field current switch, for turning on or off the current driver resident on the alternator for sending current in field coil 42. Alternatively, driver 26 may comprise a switch and a current driver to send current through the field coil 42. In this manner, alternator 30 may be individually responsive to an associated control signal 32 that, being inter-operative with the output stage of its associated voltage regulator, will drive its field coil 42 to produce electrical power.

[0022] The major components within voltage regulator 10 communicate with the processor and each other either via a bus 28 or by direct connection (point to point). Further, a variety of signals may be present in the system such as voltage, current, frequency, amplitude, or pulse width modulated signals. Examples of these signals shown in FIG. 1 include the control signal 32, feedback voltage 34, output 36, and line 38. As shown in FIG. 1, these signals are represented as wired connections. Alternatively, one, some, or all of these signals may be replaced with wireless connections. Further, the signals, including the control signal 32, feedback voltage 34, output 36, and line 38, may be analog or digital.

[0023] Referring to FIG. 2, there is shown an exemplary block diagram of multiple voltage regulator – alternator combinations as shown in FIG. 1 with the alternators electrically connected in parallel. Any number of voltage regulator – alternator combinations may be included in the system. For example, as few as two combinations or as many as "N" combinations, as shown in FIG. 2, may be included in the system. While the voltage regulators 10 are shown in FIG. 2 as separate components, multiple voltage regulators may be located within a single housing, or on a single circuit or processor. Further, the alternators in the system may be connected to the same source of motive power (such as a single crankshaft), or may be connected to different sources of motive power (such as separate crankshafts).

[0024] As discussed in more detail in FIG. 5, each of the voltage regulators 10 may act as a master regulator or as a follower regulator. Specifically, one of the

voltage regulators 10 in the system may be designated as the master regulator and the remainder regulator(s) may be designated as follower regulator(s). The communication to determine which regulator acts as the master and which regulator(s) act as the follower(s) may be conducted via line 38. For example, an arbitration process to determine the master regulator may be performed via line 38.

[0025] Once the master and follower regulator(s) are determined, they communicate with one another via line 38. The master regulator may send signals to the follower regulator(s) for control of the alternators associated with the follower regulators. As discussed in more detail below, the sensed feedback sent to the master regulator and operating characteristics of one, some, or all of the alternators may be used to generate signals to control the alternators. The signals to control the alternators may be based on a variety of factors, such as: (1) sharing the load in proportion to the output ratings of the alternators; (2) determining the load based on temperature of one, some or all of the alternators; (3) determining the load based on efficiency of one, some, or all of the alternators; or (4) determining the load based on accumulated operational life of one, some, or all of the alternators. These various determinations are discussed subsequently with respect to FIGS. 5 and 6.

[0026] If each of the follower regulators receives the same message, a broadcast message may be sent from the master regulator on line 38 indicating the contribution of each alternator. For example, the master regulator may format the broadcast message as an instruction representing a percentage contribution of the alternator's maximum output. The instruction may be a digital or analog instruction. Further, the instruction may include a number from 0 to 100, with 0 signifying zero percent contribution of the alternator's maximum output and 100 signifying 100% of the alternator's maximum output. Or, the instruction may be a number which may signify a percentage, such as in a system with 0 to 5V, with a 2.5V instruction indicating a 50% contribution.

[0027] Alternatively, the follower regulators may receive different messages from the master regulator. In one aspect, the master regulator may send a series of

messages, with each message including an address field. The follower regulators may review the address field to determine if the specific message is addressed to the particular follower regulator. In a second aspect, the master regulator may send one broadcast message which includes a look-up table. The look-up table contains a listing of the follower voltage regulator and the corresponding contribution of its respected alternator. After receiving a message from the master voltage regulator, the follower regulator(s) may send a message acknowledging receipt. Further, the message sent by the master regulator may include fault codes that communicate the fault status of the master regulator. Fault codes may include whether an alternator's shaft is not turning or whether an alternator has a fault.

[0028] FIG. 2 further shows diagnostic tool 48. Diagnostic tool 48 may communicate with the regulators in the system by connecting to line 38 via port 49. Diagnostic tool 48 may be used during testing of the regulator-alternator system or during operation of the regulator-alternator system. Moreover, diagnostic tool may be a passive device during testing or operation of the regulator-alternator system, such as by merely tapping into line 38 and listening to the communication traffic on line 38. Alternatively, diagnostic tool 48 may be an active device during testing of the regulator-alternator system. For example, diagnostic tool 48 may send commands on line 38 to regulators 10 in the system in order to simulate operation in the field.

[0029] FIG. 2 shows a parallel operation of multiple alternators connected to at least one source of motive power. Other parallel operations of two or more sources of electric power, wherein each source of power is independently regulated, may exist in a variety of situations. For example, the electrical output of two or more fuel cells may be operated in parallel to supply power to a common electrical system, and each regulator may control the fuel cell output voltage. Discrete differences in voltage control may occur when two or more devices that generate electric power are independently controlled. Thus, parallel operations of two or more sources of electric power may be controlled by the teachings of the present application.

[0030] Referring to FIG. 3, there is shown an exemplary block diagram of a single voltage regulator controlling multiple alternators, with the alternators electrically connected in parallel. Instead of a master – follower voltage regulator configuration, as shown in FIG. 2, a single regulator may be used which controls each of the alternators in the multiple alternator system. Voltage regulator 50 sends a signal to each of the drivers 26, as shown in FIG. 3. Voltage regulator 50 includes similar functionality to voltage regulator 10, as shown in FIGS. 1 and 2. Specifically, voltage regulator 50 includes processor 20, memory 22, signal conditioning interface 23, communication interface 24, and bus 28. Voltage regulator 50 further includes a multiplexer 52 which communicates with multiple drivers 26. As shown in FIG. 3, voltage regulator 50 is outlined by a dotted line to include drivers 26. The voltage regulator 50, including drivers 26, may be located within a single device, such as a single integrated circuit. Alternatively, drivers 26 may be physically located separately from the remainder of voltage regulator 50. For example, the drivers 26 in FIG. 3 may be located proximate to the alternators 30.

[0031] As discussed above with respect to FIG. 1, driver 26 may comprise a switch if the current generation is resident in alternator 30. Alternatively, driver 26 may comprise a switch in combination with a current generator. Multiplexer 52 may be connected to each of the drivers 26 via separate electrical connections, as shown in FIG. 3. In this manner, voltage regulator 50 may control each driver 26 individually. Alternatively, multiplexer 52 may be replaced with a single control line between bus 28 and drivers 26. The single control line may be used to each of the drivers 26 in unison. Further, voltage regulator 50 may receive the feedback voltage 34 and outputs 36 (such as ambient temperature, operating temperature, speed, etc.) for each alternator 30 via signal conditioning interface 23.

[0032] Referring to FIG. 4, there is shown a graph of time versus output current for two of the alternators shown in FIG. 2. As shown in the figure, OUTPUT1 for alternator 1 and OUTPUT2 for alternator 2 sum to TOTAL OUTPUT. Because of the common control of the alternators, the outputs of the

respective alternators are constant and predetermined, as shown by the constant output of OUTPUT1 AND OUTPUT2. Between time t1 and t2, the master control regulator has switched the ratio for the outputs for each of the alternators. Though, as shown in FIG. 4, TOTAL OUTPUT has remained constant.

[0033] Referring to FIG. 5, there is shown an exemplary flow diagram of operation of the multiple voltage regulator – alternator combinations shown in FIG. 2. As shown at block 60, a regulator is powered up. In one aspect of the invention, each regulator may be a master or a follower regulator. In this aspect, the regulators may communicate with one another to determine which regulator is the master regulator. As discussed above, the determination whether a specific regulator is a master or a follower may be determined prior to power up, such as a hardwired switch or a software command configuring the regulator to be a master or a follower. Alternatively, the determination whether a specific regulator is a master or a follower may be determined dynamically after power up. In either configuration, the regulators communicate with one another to inform or decide which regulator is the master regulator.

[0034] One method of dynamic determination is through an arbitration process. The regulators may decide, through signaling amongst themselves, which regulator is the master and which regulator(s) is/are the followers. In the instance where an arbitration process determines whether a regulator is a master or a follower, the regulator after power up sends a signal via line 38 to other regulators to determine if there are any other regulators operating, as shown at block 62. If there are no other regulators operating, the regulator operates its associated alternator in an independent mode, as shown at block 64. The regulator periodically may check to determine if another regulator is powered up by looping back to block 62.

[0035] If there is another regulator operating in the system, the regulators may arbitrate which will be the master regulator, as shown at block 66. This arbitration may be determined in a variety of ways. One way is to include a random number or a random number generator in each of the regulators. Upon a regulator's sensing another regulator in the system, the random number may be accessed.

Alternatively, the random number generator may generate a random number dynamically. The regulator may then wait for a time period based on random number, after which it may broadcast that it is the master regulator if the regulator has not received a similar broadcast prior to that point. For example, a random number may be generated between 0 and 10,000. The random number is multiplied by the time of transmission of a signal between regulators. For example, if the time of transmission is .001 seconds, and the random number is 152, the wait time is .152 seconds. In this manner, if another regulator has a random number of 153, the difference between wait times is at least .001, thus avoiding a possible collision of signals. After the wait time, the regulator may transmit a broadcast message to other regulators in the system declaring that it is the master regulator. This "quick draw" method allows the first regulator to send the broadcast message to declare itself the master regulator.

[0036] Another method of arbitration is to select the master regulator based on location, such as the regulator closest to the desired point of voltage regulation. In this scheme, the regulators (not yet arbitrated as master or follower) initially send out the measured voltage value at the alternator or other point to which they are connected. The highest measured value for each individual alternator or regulator suggests the closest proximity to the battery pack or storage device and this regulator therefore "wins" the arbitration process and is designated the master regulator. This scheme has the benefit that the master regulator is arbitrated as the regulator closest to the battery pack and therefore the voltage it measures may be the most appropriate for control of overall desired system voltage. Alternatively, the regulator measuring the lowest voltage may be selected as the master regulator to ensure that even the lowest measured voltage in the system is above a predetermined level.

[0037] In still another method of arbitration, a mathematical or statistical process may be used to arbitrate and select a master regulator based on measured voltages such that the regulator with the voltage closest to the mean, median or mode voltage of all those measured may be selected as master. This has the benefit that the system may be automatically configured to regulate the mean,

median or mode voltage of the entire system. Any of these voltage based arbitration schemes may further be augmented by the addition of a random number scheme in order to arbitrate between regulators measuring the same voltage in their voltage arbitration scheme alone.

[0038] Once arbitration has taken place the master regulator may remain as master for the duration of the present period of operation, *i.e.*, until the electrical or mechanical power to the system is removed or becomes unusable. Alternatively the master regulator may remain as master for a predetermined period of time or until a predetermined set of conditions are met at which point the arbitration process is repeated and a new master regulator may be selected or the master regulator commands a follower regulator to become master regulator. When using voltage as determining the arbitration, the master regulator, and therefore the primary point of voltage reference for the electrical system, may on average move to each available point of voltage regulator in the system. This has the benefit that if the master regulator is arbitrated as being the regulator furthest from the desired point of overall system voltage regulation, this situation does not dominate for an entire period of operation. The exact conditions under which a master regulator may force re-arbitration and become follower can be tailored to suit the requirements of each individual application.

[0039] After which, the operation of the regulator depends on whether the regulator is a master or follower, as shown at block 68. The master regulator may typically operate by using a voltage-controlled current source to force a fixed voltage to appear at the output of its associated alternator. Control circuitry in the processor 20 of the master regulator monitors or senses the output voltage, as shown at block 70. As discussed above, the sensed feedback may be taken at any point within the system, such as the output of the alternator associated with the master regulator, an output of another alternator, or the output of the storage device.

[0040] Based on the sensed voltage, the control circuitry in the master regulator may determine a control signal for the current source (as required by the load) to hold the alternator output voltage at the desired value, as shown at block

72. The output voltage for the alternator may be controlled using a feedback loop, which may require compensation to assure loop stability. Further, the master regulator may require a finite amount of time to correct the output voltage after a change in load current demand. For example, the current demand for the alternators may change, such as by turning on the air conditioning, requiring the regulator to adjust the current output of the alternators. This time lag defines the characteristic called transient response, which is a measure of how fast the regulator returns to steady-state conditions after a load change.

[0041] One example is a control signal which signifies a percentage of the on-time for its associated alternator. Specifically, the control circuitry for the regulator may produce a control signal between 0 and 5000. The values in this range represent the normalized on-time for a regulator. A 3000 value for a control signal indicates that the control circuitry in the master regulator determines that its associated alternator produce to turn the alternator on 60% of the time.

[0042] The regulating signal for the alternator associated with the master regulator is generated, as shown at block 76. As discussed in more detail in FIG. 6, the regulating signal may be the control signal generated by the master regulator. Alternatively, the control signal may be modified based on the operational characteristic(s) of one, some, or all of the alternators.

[0043] The signal(s) for the follower regulator(s) are also generated, as shown at block 78. As discussed in more detail in FIG. 6, the signal(s) for the follower regulator(s) may be the control signal or may be based on the control signal. For example, the control signal may be normalized and the normalized control signal may be sent to the follower regulators. As another example, the control signal may be modified based on the operating characteristics of one, some, or all of the alternators, and the modified control signal may be sent to the follower regulator(s). If the master regulator modifies the control signal based on the operating characteristic(s) of the alternator associated with the master regulator, the master regulator may receive the operating characteristic(s) via line 36. Moreover, if the master regulator modifies the control signal based on the operating characteristic(s) of the alternator associated with a follower regulator,

the master regulator may receive these operating characteristics via the follower regulator through the communication interface 24. After which, the signals are sent to the follower regulators, as shown at block 76.

[0044] The master regulator may receive an acknowledgment from the follower regulator(s). The acknowledgment may indicate whether the follower regulator(s) have implemented the signal from the master regulator or whether the follower regulator(s) are operating in independent mode.

[0045] As a follower regulator, the follower regulator receives the signal from the master regulator on the communications interface, as shown at block 82. If the follower regulator does not receive the signal from the master regulator, the follower regulator may operate in independent mode, as discussed below. For example, if the follower regulator does not receive the signal within a predetermined time, the follower regulator may assume that the master regulator has malfunctioned or that communications between the master and follower regulator have been severed. If this occurs, the follower regulator operates independently of other regulators in the system.

[0046] After receiving the signal from the master regulator, the follower regulator may then acknowledge receipt of the signal, as shown at block 84. Further, the follower regulator may determine the operational characteristic(s) of the alternator associated with the follower regulator, as shown at block 86.

[0047] The follower regulator may determine whether the command signal for the follower voltage regulator is appropriate for its respective alternator, as shown at block 88. In one embodiment, the follower regulator does not merely accept the command of the master voltage regulator. Rather, the follower regulator reviews the command to determine if it is acceptable to operate its associated alternator in such a manner. In this way, the follower regulator may independently verify that the command from the master regulator is within acceptable parameters. One manner is for the follower regulator to sense the output for its associated alternator via line 34. Similar to the master regulator, the follower regulator may use control circuitry to generate a control signal. The command of the master regulator may be compared with the control signal generated by the control circuitry of the

follower. If the command is outside predetermined guidelines, the command may be rejected. Thus, based on the sensed feedback, the follower regulator may independently verify that the command from the master regulator is acceptable. For example, if the alternators are connected in combination with a 24V battery, the sensed output voltage from the follower alternator is less than 24V, and the command from the master regulator is to reduce the current output of the alternators, the follower regulator may reject this command. Specifically, the follower regulator may determine that, based on the sensed feedback, an increase in the current output of the alternator is required. Another manner of verification is by examining the associated alternator's rated operational guidelines. Typically, an alternator has rated operational guidelines based on its operational characteristics. For example, the alternator may include maximum allowable output based on temperature (ambient and/or alternator temperature), speed, etc. These operational guidelines for the alternator may be in the form of a look-up table and stored in the memory 22 of the follower voltage regulator. Based on the operational characteristics of the alternator, the follower regulator may determine whether the signal sent from the master regulator is within the rated operational guidelines. For example, if the master regulator commands that the follower regulator send a control signal to its associated alternator to operate at 100% output, and based on the current speed and temperature of the alternator, the rated operational guidelines provide that 75% is the maximum allowable output, the follower regulator may reject the command of the master regulator and operate in independent mode.

[0048] If the signal sent from the master regulator is not acceptable, the follower regulator may then operate independently, as shown at block 90. In this mode of independent operation, the voltage regulator, previously a follower voltage regulator, operates its associated alternator by sensing the feedback via line 34. The voltage regulator may further receive operational characteristics of its associated alternator via line 36. Based on this input, the control circuitry in the voltage regulator may control the operation of the alternator via its driver 26. The voltage regulator may notify the master regulator of its independent operation, as

shown at block 86. As shown in FIG. 5, once a follower regulator operates in independent mode, it may continue to operate independently. Alternatively, the follower regulator may continue to receive commands from the master regulator and accept or reject the commands based on independent verification.

[0049] In an alternate embodiment, upon determining that the signal from the master regulator is not appropriate, the follower regulator may send a command signal to the master regulator indicating that the follower regulator will become the master regulator. Alternatively, or in addition, the follower regulator may command the master regulator to control its associated alternator. In this manner, the follower regulator may compensate for a potential failure in the control circuitry of the master regulator.

[0050] If the signal from the master voltage regulator is acceptable, the follower voltage regulator controls its respective alternator based on the signal and based on at least one operational characteristic of its associated alternator, as shown at block 92.

[0051] Referring to FIG. 6, there is shown an exemplary flow diagram for determining the signals for the master and follow regulators at block 74 of FIG. 5. As a precaution, the temperatures of one, some, or all of the alternators may be checked to determine if the operational temperatures of the alternators is above a maximum limit, as shown at block 100. The master regulator may check the temperatures for its associated alternator and the follower alternators, if the master regulator receives the temperature data. Alternatively, each regulator (master and follower(s)) may check the temperature for its associated alternator. Further, the check of temperatures may be performed at any point when controlling the alternators.

[0052] Alternatively, trends of the temperatures of one, some, or all of the alternators may be analyzed. The trend analysis may be based on the most recent temperatures of the alternators, which may be stored in the master voltage regulator memory. Trend analysis may extrapolate to determine if the alternator will operate outside of its rated range or may determine if the rate of increase in temperature is outside of acceptable limits. If one of the alternators temperatures

is above its maximum rated limit, the alternator is shut down, as shown at block 102. Alternatively, rather than shutting down the alternator, the alternator may operate at a predetermined percentage of its capacity, such as 50% of its rated output.

[0053] As shown at block 104, the master voltage regulator determines the current requirements based on control circuitry in the master voltage regulator. As discussed above, the control circuitry generates a control signal. Depending on the mode of operation, the master voltage regulator may generate a regulating signal for its associated alternator: (1) based on the control signal; (2) based on the control signal and operating characteristic(s) of its associated alternator; or (3) based on the control signal and operating characteristic(s) of the alternators in the system (including its associated alternator). Likewise, depending on the mode of operation, the master voltage regulator may generate signals to send to the follower regulators: (1) based on the control signal; (2) based on the control signal and operating characteristic(s) of its associated alternator; or (3) based on the control signal and operating characteristic(s) of the alternators in the system (including its associated alternator). The follower regulator may generate regulating signals for its associated alternator: (1) based on the signal from the master regulator; or (2) based on the signal from the master regulator and operating characteristic(s) of its associated alternator.

[0054] The master regulator may determine the mode of operation, as shown at block 106. There may be several modes of operation, as shown in FIG. 6, including operating based on the maximum rated output of the alternators, operating based on the efficiency of the alternators, or operating based on the operational life of the alternators. Other modes of operation are possible.

[0055] Operating based on the maximum output of the alternators enables the dividing of the load amongst the alternators based on maximum output. As discussed in the background section, the operating conditions for the alternators vary based on many factors including temperature, speed, etc. Thus, one alternator may operate differently from another alternator in the same system. Two alternators may receive the regulating signal, but produce different

percentages of their respective rated output. For example, the regulating signal may be 3000 (from a range of 0 to 5000). Even though the designed operational characteristics of the alternators may be the same, because the current operating characteristics of the alternators may be different, a first alternator may operate at 55% of its rated maximum with a regulating signal of 3000 while a second alternator may operate at 50% of its rated maximum at the same regulating signal. Instead, when operating in a mode based on the maximum output, the regulating signal for each of the alternators is generated such that the percentage of maximum output of the alternators is the same (e.g., 55% for each alternator). In this manner, the operation of the alternators in the system may equally contribute based on the percentage of maximum output.

[0056] There are a variety of methods for generating regulating signals for each of the alternators so that the percentage of maximum output of the alternators is the same or approximately the same. One method is to receive the control signal from the control circuitry of the master regulator and determine, based on the control signal, what the percentage of maximum output is if the control signal is sent as a regulating signal to the master alternator, as shown at block 108. Regulating signals may be generated for each of the follower alternators such that the output for the follower alternators is the same percentage of their maximum output as the master alternator, as shown at block 110. The percentage of maximum output for the master regulator may be determined via a look-up table for the master alternator. The look-up table, which may be stored in memory 22, may contain percentages of maximum outputs for certain regulating signals, speeds, and temperatures. By inputting the control signal, the speed and the temperature of the alternator, the percentage of maximum output may be determined for the master alternator. Alternatively, the table may contain percentages of maximum outputs for certain regulating signals and speeds. Temperature of the master alternator may be taken into consideration in a separate table. The determined percentage of maximum output may be sent as the signal from the master regulator to the follower regulator(s). The follower regulator may then access its own look-up table for its alternator to generate the proper

regulating signal in which to operate at the determined percentage of maximum output, for the speed and temperature of the follower alternator. For example, if the control circuitry for the master regulator generates a control signal of 3000, which translates, based on the look-up table, speed and temperature of the master alternator, 55% of the maximum rating. The 55%, or a signal based on the 55%, may be sent to the follower regulator(s). The follower regulator may generate a regulating signal, such as 3200, by accessing its look-up table, speed and temperature of its associated alternator, to produce a 55% output of the maximum rating for the follower alternator.

[0057] Operating based on the efficiency of the alternators enables the dividing of the load amongst the more efficient alternators. Operating characteristics of an alternator, such as speed and temperature, determine the efficiency of an alternator. For example, at high speed operation, the efficiency of the alternator operation is reduced. The master regulator may receive the temperature and speed information for its associated alternator and other alternators in the system, as shown at block 112. The master regulator, which may access look-up tables for each of the alternators, may then determine the efficiency of its associated alternator and other alternators in the system, as shown at block 114. Alternatively, both master and follower regulators may calculate the efficiency of its associated alternator. The follower regulators may sense the operating characteristics to calculate efficiency, such as speed and temperature, and access their look-up tables to calculate the efficiency. This calculation for the follower regulators may be sent to the master regulator via line 38.

[0058] Based on the efficiencies of the master and the follower alternators, the master regulator may generate a regulating signal for its associated alternator, and may send a signal to the follower regulator(s). The follower regulator may generate a regulating signal for its associated alternator based on the signal from the master regulator. The master regulator may determine which alternator is the most efficient and generate a signal which would control the alternator to produce a majority, most, or all of the power needed.

[0059] Operating based on the operating life of the alternators enables the dividing of the load amongst the newer, or more recently serviced, alternators. The calculation of the operational life of the alternators (either the total life of the alternator or the life of the alternator since last serviced) may be performed by the master regulator. For example, the master regulator may maintain a log of the total operation of its associated alternator and other alternators in the system. Alternatively, the calculation of the operation life of an alternator may be calculated by the associated regulator. Follower regulators may send this calculation to the master regulator via line 38.

[0060] After the operating life of the alternators is determined, as shown at block 118, the signals for the master and follower regulators are determined based on the operating life, as shown at block 120. For example, the master regulator may generate signals whereby alternators with a greater remaining operating life may bear a greater portion or all of the load.

[0061] While this invention has been shown and described in connection with the preferred embodiments, it is apparent that certain changes and modifications in addition to those mentioned above may be made from the basic features of this invention. In addition, there are many different types of computer software and hardware that may be utilized in practicing the invention, and the invention is not limited to the examples described above. The invention was described with reference to acts and symbolic representations of operations that are performed by one or more electronic devices. As such, it will be understood that such acts and operations, include the manipulation by the processing unit of the electronic device of electrical signals representing data in a structured form. This manipulation transforms the data or maintains it at locations in the memory system of the electronic device, which reconfigures or otherwise alters the operation of the electronic device in a manner well understood by those skilled in the art. The data structures where data is maintained are physical locations of the memory that have particular properties defined by the format of the data. While the invention is described in the foregoing context, it is not meant to be limiting, as those of skill in the art will appreciate that the acts and operations described may also be

implemented in hardware. Accordingly, it is the intention to protect all variations and modification within the valid scope of the present invention. It is intended that the invention be defined by the following claims, including all equivalents.